Heretical Ideas that led to the Search for the Higgs Boson

or - Job Creation in Particle Physics!

G. S. Guralnik

Brown University

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- *“Many of the current tools of Theoretical physics were known in the early 60’s but calculational methods primitive*
- Quantum field theory combined with coupling constant perturbation theory and Renormalization theory (a way to handle inevitable infinities) brilliantly described ELECTROMAGNETISM
- BUT: Coupling constant perturbation theory did not work for STRONG INTERACTIONS!
- BUT: Renormalization theory did not work for the then current theory of WEAK INTERACTIONS!
- Quantum Field Theory was thought to have failed because we could not explain the weak or strong interactions!
- It seemingly was totally forgotten that the exact theory is NON-LINEAR and will have many solutions!

- Nambu launched the study of spontaneous symmetry breaking of an internal group through his work on the BCS model (1960) and the Nambu, Jona-Lasinio model with the interaction

$$g\left[(\bar{\psi}\psi)^2-(\bar{\psi}\gamma_5\psi)^2\right]$$

- This interaction is not renormalizable in coupling constant perturbation theory!
- NJL studied this model by imposing a constraint that seemed to be inconsistent with its symmetry and then formulated a new (not coupling constant perturbation theory) leading order approximation.
- The results included a zero mass pseudoscalar (now called the Nambu-Goldstone) boson.

- This was a real breakthrough!
- This solution is a new and very different and definitely not perturbative in the coupling!
- A beautiful new concept - a theory can have equations with a symmetry but its solutions need not have this symmetry!
- This result demonstrated that Quantum Field Theory still had enormous untapped predictive power!

- How is this “spontaneous symmetry breaking” induced?
- suppose a theory has a conserved current associated with a symmetry such that $\partial_\mu J^\mu = 0$.
- Assuming that surface integrals can be neglected, it follows that there is a time independent charge:

$$Q = \int d^3x J^0$$

- Perturbative (in the coupling) solutions require that the vacuum (the state of lowest energy) is a (null) eigenstate of this charge, but these new solutions require that

$$Q|0\rangle \neq 0\,.$$

- Further, it is (normally) required that:

  $\langle 0|[Q, some - local - operator(\vec{x}, t)]|0\rangle = (\text{non-zero consta}$

- Any solution we find must be consistent with this constraint.
- THIS IS A SIGNIFICANT CONSTRAINT WITH MAJOR CONSEQUENCES!
- It, in effect, imposes boundary conditions on the solution which do not respect the symmetries of the lagrangian and the equations of motion.
- This is something that occurs all the time when looking at solutions to normal differential equations!

- After the NJL papers, J. Goldstone wrote (1960) his famous paper where he examined a two (real) component scalar field theory with a quartic self interaction.
- This interaction has a conserved charge symmetry which is dynamically broken by requiring that the vacuum expectation of the scalar field is a non-vanishing number.
- In the leading approximation there are two scalar particles - one with zero mass.
- In 1962 Goldstone Salam and Weinberg proved that the spontaneous breaking of a continuous global symmetry in a relativistic theory requires associated zero mass excitations.
- THIS IS NOT A GOOD THING! THERE IS ONLY ONE OBSERVED ZERO MASS PARTICLE!

- ARE THESE NEW SOLUTIONS GOOD FOR ANYTHING? Did not look like it!

- Weinberg recently described how we felt. He compared this to the feeling a child has when finding a hidden cupboard filled with jars of jam and then discovering that the jam is poisoned!

- BUT perhaps there was one application. Schwinger had recently argued that there was no reason beyond the smallness of the coupling constant and the use of perturbation theory that the photon must have zero mass.

- Could we at least use this discovery to show that there is a dynamical reason for the one (observed) massless particle -the photon- to have zero mass?

- This is where I come in: After Bjorken gave a talk (1962) at Harvard, my thesis advisor, Walter Gilbert (Nobel Laureate Chemistry 1980), suggested that I look at Bjorken's proposed model of E&M — a variant of the Nambu-Jona-Lasinio model with interaction

$$g\,(\bar{\psi}\,\gamma^{\mu}\,\psi)\,(\bar{\psi}\,\gamma_{\mu}\,\psi)\,.$$

- The current is required to have non-vanishing vacuum expectation.
- The symmetry that is broken is Lorentz symmetry — relativistic invariance.

- I showed that BJ's basic conclusion that this theory is equivalent to QED is correct. Careful calculation shows that the Lorentz symmetry breaking is trivial and does not manifest itself in a physically observable way.

- This was enough for a nice Ph.D. thesis!

- But I was not smart enough to leave "good enough" alone!

- Despite the fact that Schwinger had argued that there was no dynamical reason for the photon to have zero mass, I thought from the arguments made for the Bjorken model that I could construct a symmetry breaking argument that would require massless photons in conventional E&M. This argument was wrong and, fortunately, Coleman detected this in my (1963) thesis presentation.

- I removed the offending chapter in the final version.

Picture taken much later than 1960's. In the 1960's Coleman wore purple velvet suits! Photo by Lubos Motl

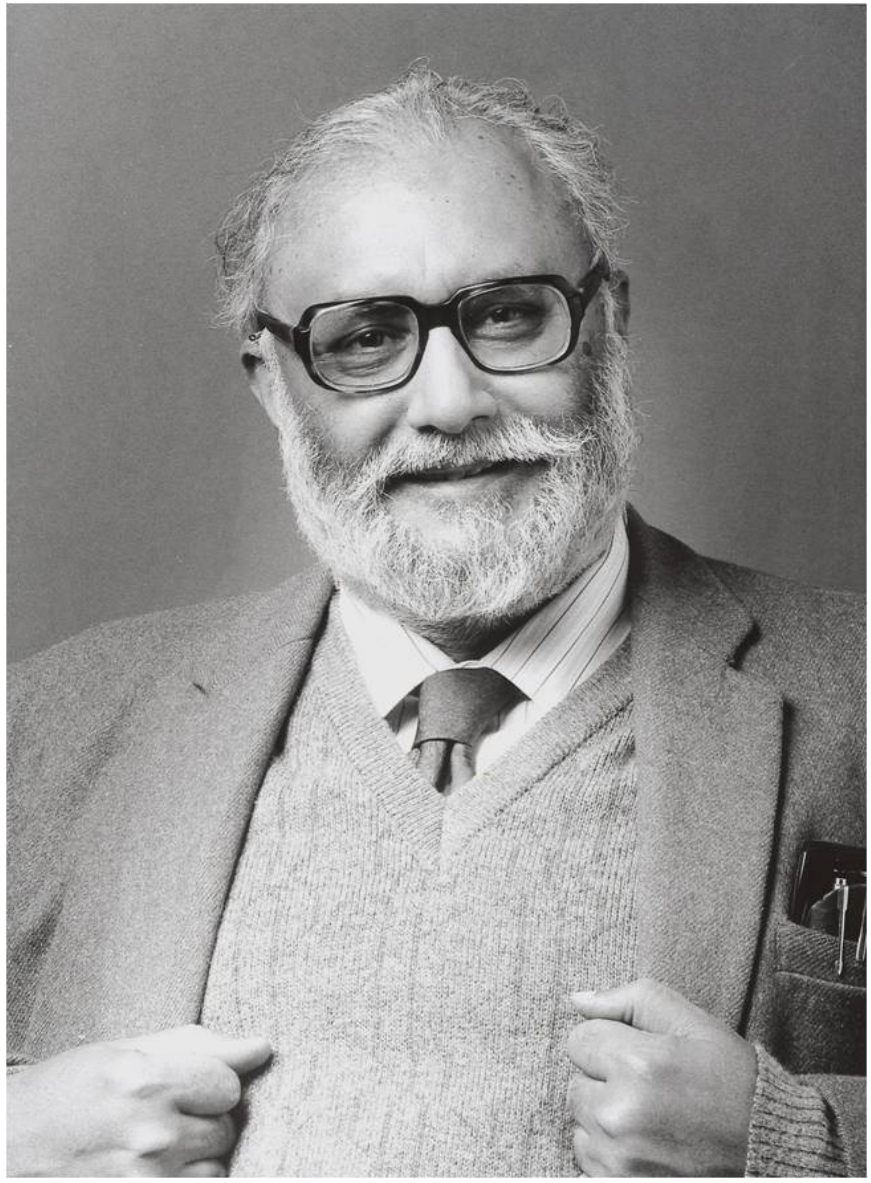
- During my time at Harvard, I was talking with Dick Hagen – an undergraduate friend at MIT and then a Physics graduate student at MIT and already my co-author on our first physics research paper.

- We always worked very hard - particularly in the study of applied mechanics!

A Working Afternoon: Young Baron May of Oxford, Guralnik and Hagen 1961

- In 1963 Hagen took a postdoctoral position at the University of Rochester (and is still there).
- We continued collaborating
- He became interested in complicated expensive and unreliable but beautiful machinery.
- Also on how to minimize living costs
- I thought he might be thinking of becoming an experimentalist

- I went to Imperial College (after being rejected by CERN) at the beginning of 1964 with a new NSF postdoctoral fellowship.
- IC was probably the best High Energy Theory place in the world at that time and I met a fantastic bunch of physicists there. The ones I interacted with the most were Tom Kibble, Ray, Streater, John Charap, and to a lesser degree Paul Matthews and Abdus Salam.



Abdus Salam

Salam and Kibble -like the Harvard and MIT crowd, the IC people were very serious

- Despite my embarrassing thesis exam, I STILL BELIEVED THAT THERE MUST BE A DYNAMICAL REASON THAT THE (USUAL) PHOTON OF QED WAS MASSLESS!
- After a lot of thought I produced a NEW AND BRILLIANT PROOF of this the Nambu Goldstone theorem!
- I wrote a paper (in April 1964) - my first from I.C. - and sent it to Physical Review Letters.
- After a couple of days, I realized that while brilliant - my proof was WRONG in the only case that mattered - RADIATION GAUGE QED!
- HOW COULD THIS BE? MY ONLY ASSUMPTION WAS THE VALIDITY OF THE NAMBU GOLDSTONE THEOREM!
- OBVIOUS CONCLUSION - THERE IS SOMETHING VERY WRONG WITH using THE NAMBU GOLDSTONE THEOREM!

- Some work leads to a SURPRISING FACT - The (VERY STRANGE) CHARGE that is "broken" LEAKS OUT OF ANY VOLUME NO MATTER HOW BIG!
- THERE IS NO TIME INDEPENDENT CHARGE SO THERE IS NO NAMBU GOLDSTONE THEOREM!
- CONSEQUENTLY, THERE IS NO CONSTRAINT OF ANY KIND ON ANY MASS OF THE THEORY.
- In “relativistic” gauges the charge is conserved, but the massless Nambu Goldstone boson are gauge particles!
- The Nambu Goldstone theorem says nothing here about physical particles!
- OOPS - ANOTHER WRONG PAPER!
- IT WAS CLEAR THAT THERE WAS A BRAND NEW GAME TO PLAY!

- I caught this error in a couple of days but through a series of unlikely events, this paper was received by P.R.L. on June 1 1964 and published!
- This is actually an important paper! It is the first in the series that led to the prediction of the “Higgs Boson”
- Ironically, Peter Higgs sent a paper to Physics Letters -received July 27, 1964 and in it he makes the exact same subtle error.
- As can happen with wrong proofs - he comes to a different but unjustified conclusion- but one now more to everyone’s liking.
- Though WRONG, this Peter Higgs’ Physics Letter paper is very famous!

- Summary of my results: It is not possible to prove that the photon is massless because of restrictions from dynamics!
- The Goldstone theorem only requires that gauge excitations are massless. (WORTHLESS)
- These are very general statements: The Nambu-Goldstone theorem does not require physical zero mass states in any gauge theory including non abelian theories.
- In gauge theories, the Goldstone bosons are always nonphysical gauge excitations!
- THESE STATEMENTS CONSTITUTE THE ESSENCE OF THE "HIGGS MECHANISM"!
- NOTE: Higgs (or EB) DID NOT prove any of this!

- IMPORTANT: THIS RESULT IS AN EXACT OBSERVATION! It has nothing directly to do with any approximate expansion!

- With the understanding that the Goldstone theorem was irrelevant for gauge theories I, with Hagen and Kibble, prepared a paper (GHK) explaining the reason for its irrelevance and giving an explicit example which had symmetry breaking but no Goldstone bosons. All major points were worked out in detail by the end of April 1964.

- UNIQUELY THE GHK PAPER STATES AND EXPLAINS THE EXACT MODEL INDEPENDENT “HIGGS” MECHANISM! ALL OTHER RELATED WORK IGNORES THE CONSEQUENCES OF THE GOLDSTONE THEOREM OR GETS IT WRONG - THUS NOT ACCOUNTING FOR AN UNWANTED MASSLESS PARTICLE! THIS WAS THE MAJOR PROBLEM STOPPING ALL PROGRESS!

- THE SIMPLE explicit example of spontaneous breaking without a massless Goldstone boson!
- We started with the usual (FOR US-NO RENORMALIZATION COUNTER TERMS!) scalar QED Lagrangian:

$$L = -\frac{1}{2} F^{\mu\nu} (\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \phi^\mu \partial_\mu \phi + \\ + \frac{1}{2} \phi^\mu \phi_\mu + i e_0 \phi^\mu \mathbf{q} \phi A_\mu$$

$$\mathbf{q} = \sigma_2$$

$$\phi = (\phi_1, \phi_2)$$

$$\phi_\mu = (\phi_1^\mu, \phi_2^\mu)$$

- This is a very non-trivial interacting theory characterized by a conserved current. It is renormalizable in the coupling constant expansion with an induced ϕ^4 interaction. No other non-trivial ϕ^n interaction can be added to it and keep it renormalizable.

- We do not put in counter terms in accord with the conventions that Schwinger used!

- We look for solutions that break the charge symmetry by having non-vanishing scalar field expectation

- It is very natural to put in sources for the fields and attempt to find expansions by iterating in derivatives of these sources.
- A variant of this approach was used in my thesis to study the Bjorken model.
- I initially approached the problem in this manner, and satisfied myself that a consistent (with symmetry breaking) renormalizable approach existed - but never published it.
- In our GHK paper we only consider the simple lowest order symmetry breaking solution to this Lagrangian

- The leading approximation is obtained by replacing $i\,e_0\,\phi^\mu\,\mathbf{q}\,\phi\,A_\mu$ in the Lagrangian by $\phi^\mu\,\eta\,A_\mu$.
- This "reduced Lagrangian" results in the linearized field equations:

$$\begin{aligned} F^{\mu\,\nu} &= \partial^\mu A^\nu - \partial^\nu A^\mu \;; \\ \partial_\nu F^{\mu\,\nu} &= \phi^\mu\,\eta \;; \\ \phi^\mu &= -\partial^\mu \phi - \eta\,A^\mu \;; \\ \partial_\mu \phi^\mu &= 0 \;. \end{aligned}$$

- These equations are soluble, since they are (rotated) free field equations. The diagonalized equations for the physical degrees of freedom are:

$$\begin{aligned} (-\partial^2 + \eta_1^2)\,\phi_1 &= 0 \;; \\ -\partial^2 \phi_2 &= 0 \;; \\ (-\partial^2 + \eta_1^2)\,A_k^T &= 0 \;. \end{aligned}$$

- This free diagonalized form of the second equation is the source of the wrongly criticized "totally decoupled" statement in the GHK paper, more about this later!

- For convenience, we have made the assumption that η_1 carries the full value of the vacuum expectation of the scalar field (proportional to the expectation value of ϕ_2). The superscript ^{T} denotes the transverse part. The two components of A_k^T and the one component of ϕ_1 form the three physical components of a massive spin-one field while ϕ_2 is a spin-zero field.
- As previously mentioned, the Nambu-Goldstone theorem is not valid, so there is no resulting massless particle.
- If the theorem were valid, ϕ_1 would be massless.
- It is very important to realize that it is an artifact of the lowest order approximation for the above action that ϕ_2 is massless. The excitation spectrum of this field is NOT CONSTRAINED by any theorem!

- A big fuss was made about GHK in talks,social media and newspapers by a few “physicists”.
- They claim we have no Boson despite degree of freedom and the equation as above.
- OR: it has been claimed that we do not have The Boson because what we display has zero mass!
- THIS IS a MISLEADING AND INCORRECT EVALUATION.
- Our formulation starts from a different first approximation because of the way we handle renormalization counter terms but under iteration is identical to the Higgs model.
- The theory is not capable of revealing anything about the Higgs boson mass!
- This is why it was not clear where to look experimentally - only other considerations suggested a reasonable range in the actual standard model.

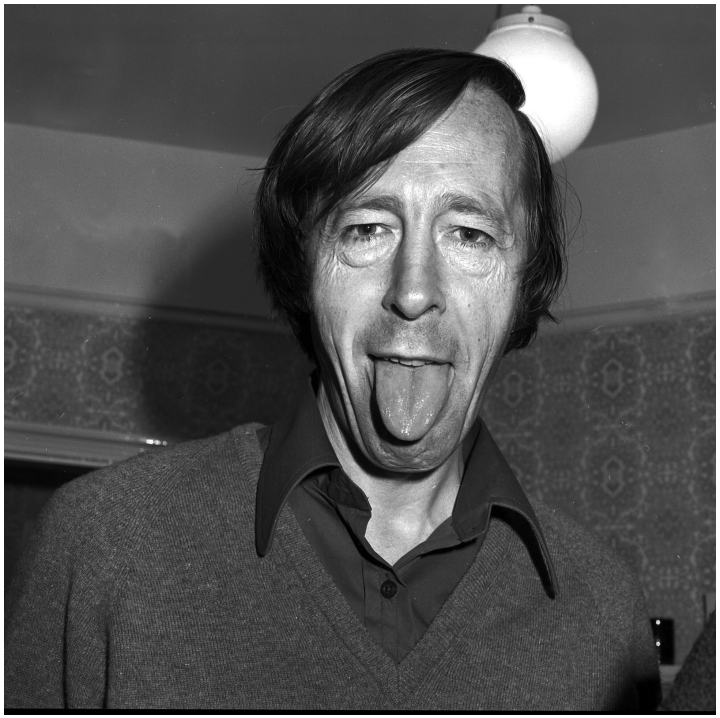
WE put this all together in the GHK paper which addresses two major issues in detail:

- It shows exactly why the gauge theories do not intrinsically require zero mass particles.
- This emphatically does not depend on a model, but is a consequence of the “leakage” of appropriate charges out of any surface
- This is a fully quantum mechanical proof.

AND

- We demonstrate this in a (non-coupling constant perturbative) self consistent leading order approximation of scalar electrodynamics.

- We were fully aware of how subtle this problem was and the fact that I had two near hits already. Thus, we were in no hurry to publish!
- Everyone who we talked to (many well known physicists) told us that this was just plain wrong!
- We wanted to get a more general understanding and we thought we had no competition.
- Finally - after running every check we could think of - we sent it to PRL (received October 12 1964).
- Published after EB and H. We saw preprints by them after our paper was finished and literally in the envelope. We thought these papers were close but fatally flawed!
- We opened the envelope and referenced EB and H. This was the correct thing to do.



WHY WE DID/DO NOT TAKE THE EBH PAPERS SERIOUSLY!
In Contradistinction to Englert and Brout and Higgs:

- The all important question was to explain why spontaneous symmetry breaking solutions of field theory could describe real world physics.
- A required zero mass physical particle means that spontaneous symmetry breaking is useless for physics.
- GHK fully explains why the Goldstone boson is a gauge only excitation in manifestly covariant formulations and is not present in the physical radiation gauge. As I said earlier - This is exact!
- EB touches, without analysis, the Nambu Goldstone boson issue but does not fully construct the lowest order approximation. They do not address the “Higgs Boson”

- The Higgs PL paper is wrong because it assumes the validity of the Goldstone theorem in the radiation gauge.
- In his PRL paper Higgs does not write down the full solution to his equations.
- Check this out! He writes down the EM equations in arbitrary gauge
- He then writes down a solution - but not the complete solution.
- He fails to observe the “zero mass” excitations which are obvious solutions to his equations! They turn out to be pure gauge but this needs proof!
- Quantum mechanics requires (because of the Goldstone theorem) that the zero mass modes must be present in manifestly relativistic gauges! Higgs leaves out this solution in his classical analysis!

- The reception of the GHK work is quite interesting: While I talked about the work informally in several places and particularly Oxford before the actual paper was released, I also gave several seminars after its release.
- I was invited to give a talk at Edinburgh almost immediately and met Peter Higgs who I found to be a pleasant and friendly person.
- My presentations were greeted with fairly uniform disbelief.

- In the summer of 1965 I gave a talk on GHK at a small conference outside of Munich, sponsored by Heisenberg.
- Heisenberg and other famous people at the conference thought these ideas were junk and made it clear that they felt that way.
- Hagen also attended, but he talked on other topics.
- Schwinger did not say a word about my talk.
- BUT - One redeeming aspect of this conference was that I got a demonstration ride in Julian Schwinger's factory fresh Iso Rivolta (Corvette powered).

- Fortunately, Dick had helped me get a job at Rochester. Rochester's high energy theory group was, as was often the case then, under the control of one senior physicist, Bob Marshak.
- Marshak, was a commanding and wonderful presence. He and George Sudarshan were the originators of the $V-A$ theory of weak interactions which was another crucial cog in the development of the unified theory of Weak Forces and Electromagnetism.
- After a few months at Rochester, Marshak called me into his office and told me that working on spontaneous symmetry breaking problems was not wise. He told me that I should work on something else if I wanted to stay in physics
- The job market was very tight: this is not a new thing!
- I obeyed. I am still sure he was correct-although I stopped work on the application to weak interactions!

- It was not until after the work by Salam and Weinberg in 1967 on the unified theory of weak and electromagnetic interactions that any of this work was taken seriously.
- GHK (and Higgs) published other related but relatively minor papers on this idea.
- We moved on to other problems.
- Until relatively recently I was never invited to talk in the U.S. on this work.
- In Europe there has been decades long of publicity of EBH particularly by Edinburgh university
- Not so for our institutions and GHK which is why our work was, until recently, almost forgotten.
- This changed with the award of the Sakurai prize of the APS to the members of the three groups

“Gang of five” Sakurai Prize 2010

There are three More Papers in this series:

- Gauge Invariance and the Goldstone Theorem, Gerald S. Guralnik, “Proceedings of seminar of unified theories of elementary particles”, July 1965
- This paper has much of the detailed discussion of items mentioned in this talk and is a significant extension in detail of the GHK paper.
- This is the writeup of my standard speech at the time. It was given at Edinburgh with Peter Higgs in the audience on November 23, 1964.
- It has recently been republished:“Gauge Invariance and the Goldstone Theorem” Jul 2011. 12 pp. Published in Mod.Phys.Lett. A26 (2011) 1381-1392 e-Print: arXiv:1107.4592 [hep-th]

- Peter Higgs in 1965 submitted to Physical Review the paper: “Spontaneous Symmetry Breakdown without Massless Bosons”, Physical Review **145**,1156 (1966). He has the correct ingredients in this paper. Much of it is similar to my Edinburgh talk and he acknowledges conversations with me. Higgs adds one element to this paper. He displays the tree graphs (not included in the PRL papers) as contributions to the next order calculation.

- In 1967 Kibble explicitly wrote up our analysis as applied to non-abelian gauge models. This work is fundamentally identical to that in our GHK paper and is covered by our original exact constructs but is closer in explicit form to the structure used in the Standard Model. See T.W.B. Kibble, “Symmetry breaking in nonAbelian gauge theories” Phys.Rev.**155**,1554 (1967)